Clinical Investigation

A Comparison of Flat-Sheet and Hollow-Fiber Membrane Oxygenators

The Shiley M-2000 vs. the Bentley BOS-CM 40

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To compare new flat-sheet and hollow-fiber membrane oxygenators for use in cardiopulmonary bypass, we randomly divided 40 coronary artery surgery patients into 2 groups of 20 patients each. The Shiley M-2000 flat-sheet membrane oxygenator was used in 1 group, and the Bentley BOS-CM40 hollow-fiber membrane oxygenator was used in the other group. Both oxygenators allowed for adequate transfer of oxygen and carbon dioxide. At the end of perfusion, the platelet counts were significantly lower and the arterial pH significantly higher in the Shiley group than in the Bentley group. The other hematologic parameters, as well as postoperative blood losses, were similar in the 2 groups, but were also similar to those reported earlier with respect to bubble oxygenators. On the basis of these results, we conclude that, for routine short-term perfusion, these new membrane oxygenator models, while marginally different from one another, offer no real advantage over bubble models. ***(Texas Heart Institute Journal 1989;16:27-31)***

With respect to the clinical complications of perfusion, comparisons of membrane and bubble oxygenators have yielded contradictory results. Clark and colleagues[1] concluded that, when used for perfusion periods lasting less than 2 hours, membrane oxygenators offer no biochemical or hematologic advantage over bubble devices. Nevertheless, these researchers reported that, during longer periods of perfusion, membrane oxygenators cause less trauma to certain blood proteins, as well as less hemolysis and less postoperative bleeding.

Recently, researchers have developed a number of hollow-fiber membrane oxygenators using microporous polypropylene fibers; these devices are held by their manufacturers to offer more clearly demonstrable advantages over the bubble oxygenator than did the older membrane oxygenators. In this report, we have chosen the Bentley BOS-CM40 hollow-fiber membrane oxygenator as representative of its kind, for direct comparison with an M-2000 "bilevel crossflow" membrane oxygenator manufactured by Shiley, Inc.,[2] which uses a flat-sheet membrane in lieu of a hollow-fiber membrane. These we examine within the context of the last decade's experience in comparing the performance of bubble and membrane oxygenators.

Key words: *Oxygenators; oxygenators, membrane; extracorporeal circulation; cardiopulmonary bypass; open heart surgery; blood gas exchange*

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Materials and Methods

The Shiley M-2000

The Shiley M-2000 (Shiley, Inc.; Irvine, California, USA) is a flat-sheet membrane oxygenator, in which 2.3 m^2 of flat polypropylene membrane is folded in Z fashion, to provide 60 blood channels and 61 gas channels. Gas exchange takes place across the membrane as blood flows from the bottom to the top of each blood channel, countercurrent to the flow of gas on the opposite side of the membrane. Nonwoven polypropylene screens inserted in each blood and gas channel serve as spacers and provide "bilevel crossflow." This term refers to the path that the blood follows: as it enters the blood channels in the membrane element, it follows a diagonal path between the strands of the screening material created by the interdigitation of the screen on the blood and gas sides—thus producing crossflow. Because it is nonwoven, the screening material creates 2 levels (Fig. 1), between which the mixing

of blood occurs. As a result of this bilevel crossflow, more red blood cells come into contact with the membrane material. The Shiley M-2000 membrane oxygenator is recommended by its manufacturer for use in adult patients of all sizes and weights.

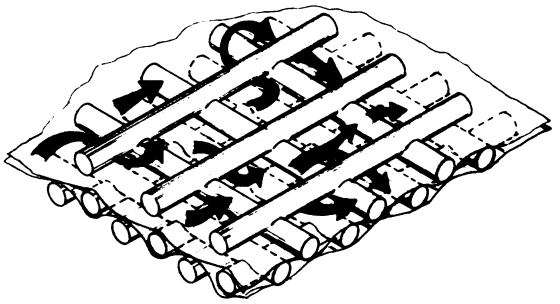

Fig. 1 A schematic representation of bilevel crossflow in the Shiley M-2000. (Courtesy of Shiley Incorporated)

The Bentley BOS-CM40

The Bentley BOS-CM40 hollow-fiber membrane oxygenator (Bentley Laboratories, Inc.; Irvine, California, USA) consists of a bundle of microporous polypropylene hollow fibers, which are encapsulated in polyurethane at both ends. As blood enters each fiber, it is surrounded by an oxygen-rich ventilating gas mixture. As the venous blood flows through the capillaries, gases diffuse across the membrane. The fiber bundle is constricted in the middle to prevent shunting of the ventilating gas. The BOS-CM40 capillary membrane contains approximately 53,000 fibers of 13.2 cm each in length, thereby providing an effective frontal surface area of 4.0 m^2. This oxygenator is recommended by its manufacturer for patients who weigh approximately 85 kg or less and whose body surface area (BSA) measures up to 2.1 m^2.

TABLE I. Distinctions between 20 Patients on Bentley BOS-CM40 and 20 Patients on Shiley M-2000 Membrane Oxygenators

	Bentley Group		Shiley Group
Age (yr)	60 ± 7.4	ns	61 ± 6.1
Weight (kg)	78 ± 8.2	ns	78 ± 11.3
Body surface area (m^2)	1.9 ± 0.1	ns	1.9 ± 0.2
Cardiopulmonary bypass time (min)	87 ± 48.5	ns	84 ± 36.4
Aortic occlusion time (min)	49 ± 33.0	ns	48 ± 21.7

ns = not significant

All values are mean ± SD (standard deviation).

Patient Population

Forty consecutive adult coronary artery surgery patients were randomized into 2 groups, each of which contained 20 patients. For cardiopulmonary bypass (CPB) during operation, the Shiley M-2000 membrane oxygenator was used in 1 group (the "Shiley" group), and the Bentley BOS-CM40 membrane oxygenator was used in the other group (the "Bentley" group). There were no significant differences between the 2 groups with respect to age, weight, BSA, duration of CPB, or aortic occlusion time (Table I).

All of the patients were anesthetized with a modified neuroleptanalgesic, supplemented by nitrous oxide and muscle relaxants. Perfusion was achieved with a roller pump (Sarns IV-V, Sarns, Inc.; Ann Arbor, Michigan, USA). Blood flow was maintained at about 50 mL/kg body weight during hypothermic bypass (esophageal temperature, 25 to 28 °C). The lungs were not ventilated during CPB. The priming solution consisted of 2000 mL of crystalloid fluid (Ringerdex, Pharmacia; Uppsala, Sweden). For myocardial protection, cold cardioplegia with a potassium concentration of 20 mEq/L was given after cross-clamping of the aorta; this solution was drained into the heart-lung machine. After an initial dose of about 10 mL/kg body weight had been administered, smaller amounts were given to maintain a myocardial temperature of below 15 °C.

Arterial blood samples were drawn into heparinized syringes and Vacutainers before the start of CPB, 10 to 15 minutes after the beginning of CPB, just before the end of CPB, and 24 hours after the start of the operation. Blood pO_2 and pCO_2 ratios were altered by adjusting the percentage of O_2 in the oxygenator; no CO_2 was administered. The average ratio of oxygen flow to blood flow was 1:1 in the Bentley oxygenator and 0.8:1 in the Shiley oxygenator; the oxygen flow rates were established by their own perfusion optimization.

Anticoagulation was maintained with heparin (300 units/kg), and the accelerated clotting time (ACT) was maintained at greater than 400 seconds throughout bypass. After CPB was finished, heparinization was reversed by administering suitable doses of protamine sulphate, based on the ACT values. The resulting data were compared by means of Student's *t*-test, and differences of $p < 0.05$ were considered statistically significant.

TABLE II. Arterial Blood-Gas Values at the Beginning and End of Perfusion

Oxygenator	pH	pO_2 (kPa)	pCO_2 (kPa)
10 to 15 Minutes into Perfusion:			
Bentley	7.39 ± 0.05	49 ± 13.4	4.6 ± 0.7
Shiley	7.42 ± 0.06	42 ± 12.4	4.4 ± 0.9
	ns	ns	ns
At End of Perfusion:			
Bentley	7.41 ± 0.05	25 ± 19.6	4.8 ± 0.8
Shiley	7.46 ± 0.10	31 ± 14.0	3.8 ± 1.0
	$p < 0.05$	ns	$p < 0.001$

Normal values: pO_2 > 10 kPa; pCO_2 = 4.5 to 6.0 kPa

pO_2 = partial pressure of oxygen; pCO_2 = partial pressure of carbon dioxide; ns = not significant

All values are mean ± SD (standard deviation).

Results

All but 1 of the 40 patients survived the coronary operation. In the case of the nonsurvivor, the cause of death was not related to the oxygenator.

Postoperative blood loss via the chest tube averaged 356 ± 127.2 mL/m² BSA per 24-hour period in the Shiley group and 341 ± 167.9 mL/m² BSA per 24-hour period in the Bentley group; these differences were not statistically significant. After 10 to 15 minutes of perfusion (Table II), there were no significant differences between the blood-gas values in the 2 groups. At the end of perfusion, the pCO_2 was significantly lower—and the arterial pH significantly higher—in the Shiley group. The blood-leukocyte counts (Table III) and blood-hemoglobin values (Table IV) did not differ significantly between the 2 groups. The plasma-hemoglobin value (indicating degree of hemolysis) per 60 minutes of perfusion was 287 ± 132.4 with the Bentley BOS-CM40 oxygenator and 248 ± 134.3 with the Shiley M-2000 oxygenator; again, differences were not statistically significant (Table V). The degree of hemolysis was slightly greater with these 2 devices than it had been with

TABLE III. Blood-Leukocyte Counts (10^9/L)

Oxygenator	Before Perfusion	10-15 Min into Perfusion	At End of Perfusion	24 Hr after Perfusion
Bentley	5.1 ± 1.5	2.9 ± 0.8	5.5 ± 2.5	11.7 ± 2.5
Shiley	5.7 ± 1.7	3.6 ± 1.9	4.9 ± 2.2	11.5 ± 2.1
	ns	ns	ns	ns

ns = not significant

All values are mean ± SD (standard deviation).

TABLE IV. Blood-Hemoglobin Values (mg/L)

Oxygenator	Before Perfusion	10-15 Min into Perfusion	At End of Perfusion	24 Hr after Perfusion
Bentley	122 ± 11.0	79 ± 8.7	83 ± 11.7	117 ± 10.8
Shiley	125 ± 15.7	82 ± 12.2	84 ± 11.3	119 ± 15.2
	ns	ns	ns	ns

ns = not significant

All values are mean ± SD (standard deviation).

TABLE V. Plasma-Hemoglobin Values (mg/L) Produced by 7 Different Oxygenators, Indicating Severity of Hemolysis

Oxygenator	Number of Patients	Per 60 Min	At End of Perfusion
Bentley BOS-CM40 (membrane)[c]	20	287	378
Shiley M-2000 (membrane)[c]	20	248	325
Shiley S-100 (bubble)[x]	100	231	340
Travenol TEFLO (membrane)[x]	23	145	294
Harvey H-1000 (bubble)[x]	38	193	280
Harvey H-200 (bubble)[x]	88	191	292
AGA (disc)[x]	361	195	286

c = coronary patients only; x = various types of adult open-heart operations (See Björk.[3])

TABLE VI. Mean Actual Blood Platelet Counts (10^9/L)

Oxygenator	Before Perfusion	10-15 Min into Perfusion	At End of Perfusion Actual	At End of Perfusion Corrected	Change	24 Hr after Perfusion
Bentley	190 ± 47.9	101 ± 34.3	129 ± 46.4	199	+ 4.7%	184 ± 68.4
Shiley	164 ± 50.6	83 ± 29.4	101 ± 37.2	149	- 9.1%	147 ± 69.6
	ns	ns	$p < 0.05$			ns

Corrected = corrected for dilution; ns = not significant
All values are mean ± SD (standard deviation).

types of oxygenators used in earlier studies at our clinic (which studies, however, had not been restricted to coronary patients). The differences might have been more pronounced if coronary patients alone had been included in the earlier studies. The blood platelet counts at the end of perfusion were significantly lower ($p < 0.05$) in the Shiley group than in the Bentley group (Table VI). When corrected for dilution, there was a slight decrease in the Shiley group's blood platelet counts and a slight increase in those of the Bentley group.

Discussion

Both oxygenators evaluated in this study provided for adequate transfer of oxygen and carbon dioxide. The Shiley M-2000 was more efficient than the Bentley BOS-CM40 and, despite having a smaller membrane surface area (2.3 m^2 compared with 4.0 m^2), required a lower O_2-to-blood flow ratio (0.8:1 compared with 1:1). In a membrane oxygenator, oxygen transfer is dependent upon many factors, including the membrane surface area, oxygen concentration, blood flow rates, hemoglobin concentration, blood temperature, and O_2 saturation level of venous blood. Carbon dioxide removal depends upon 2 variables: the diffusibility of the membrane material and the total flow rate (sweep rate) of the ventilating gases. The subnormal pCO_2 value provided by the Shiley oxygenator at the end of perfusion could have been avoided by reducing the O_2-to-blood flow ratio to still less than 0.8:1.

In both the Shiley and the Bentley models, the degree of hemolysis after 60 minutes of perfusion was relatively high compared to our earlier results with bubble, membrane, and even disc oxygenators (Table V). Blood that falls into the pericardium undergoes immediate hemolysis, to a degree much greater than that undergone by blood subjected to a bubble oxygenator; the importance of pericardial blood as the major source of hemolysis has already been emphasized.[4] Our series included coronary artery bypass patients alone, because coronary operations (in contrast to valve-replacement procedures) are associated with minimal exposure of the blood to the pericardium. If coronary patients alone had been included in our earlier studies, the differences between the results produced by the above-described membrane oxygenators and those produced by the earlier models would probably have been more pronounced. Any attempt to compare the deleterious effects of various oxygenators on blood, however, would require elimination of the pericardial factor.

In comparing our present findings with our earlier findings with the Shiley S-100 (386 mL/m^2/24 hours), *Harvey H-1000 (366 mL/m^2/24 hours), and *Harvey H-200 (420 mL/m^2/24 hours) bubble oxygenators,[3] we could not demonstrate that either the Shiley or the Bentley membrane oxygenator had any more beneficial influence on the amount of postoperative blood lost. Clark and associates[1] reported a similar lack of benefit in using membrane oxygenators for perfusion periods of less than 2 hours, but contrasting results have been reported by other investigators.[5]

Deficits in platelet number and function may be an important cause of impaired hemostasis after CPB.[6] Such deficits presumably occur after platelet interaction with the oxygenator in the extracorporeal circuit.[7] In our study, there was a reduction of platelets at the end of perfusion in both the Bentley and the Shiley models; this reduction was significantly ($p < 0.05$) more pronounced in the Shiley oxygenator (Table VI). When we corrected for hemodilution, however, by dividing each platelet count by the simultaneously measured hematocrit (platelet index), this difference became still greater, with a slight increase in the number of thrombocytes in the Bentley oxygenator and a slight decrease in the number in the Shiley oxygenator. A large decrease in platelet concentra-

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tion was already evident in both groups 10 to 15 minutes after the initiation of bypass, and this decrease could not be attributed to hemodilution alone. The loss of circulating platelets is likely to have resulted from rapid initial platelet adherence to the oxygenator's surface and/or from platelet sequestration by the liver and spleen.[8,9] Although platelet concentration increased at the end of perfusion, the cause of this increase remains unclear; 1 possible explanation is that a compensatory redistribution of platelets from organs, vessels, and bone marrow[9] took place. When Trumbull and colleagues[10] compared SciMed membrane oxygenators with various bubble devices, they found a slightly increased platelet index in both groups. These investigators stated that, with respect to the preservation of platelets, membrane oxygenators offer no advantage during CPB periods lasting up to 2 to 3 hours. Edmunds and coauthors[11] reported that platelet counts, when corrected for dilution, did not change significantly in patients perfused with membrane oxygenators but increased slightly, although significantly, in those perfused with bubble oxygenator systems. They rejected the hypothesis that membrane oxygenators cause decreased trauma to platelets during routine CPB.

Neither oxygenator used in this study produced a significant change in the white blood cell count (Table III). A decreased number of leukocytes was observed during the CPB, but an increase occurred 24 hours after the start of surgery. Similar findings have been reported before.[12,13] This decrease in the number of circulating leukocytes is attributed to activation of the complement system.[14] The lungs, bone marrow, and body temperature play important roles in leukocyte kinetics. Operations using CPB significantly affect the immunologic function of polymorphonuclear leukocytes and result in the consumption of complement.[15] In turn, decreased complement levels and impairment of polymorphonuclear leukocyte function increase the risk of infection during CPB. Experimental studies have shown that membrane oxygenators are superior to bubble oxygenators in maintaining the normal host-defense mechanism.[16] It has not yet been proved, however, that the use of a membrane oxygenator reduces the risk of infection.

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